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published in
Motor control
1999

DOI (link to publisher)
10.1123/mcj.3.2.105

document version
Publisher's PDF, also known as Version of record

Motor Control, 1999, **3**, 105-134

Discovering the Right Questions in Motor Control: Movements (1929)

Anatol G. Fel'dman and Onno G. Meijer

The article "Movements" was written by Bernstein for the *Grand Medical Encyclopedia*. Rather than presenting a specialized account of his science, Bernstein primarily wanted to inform a broad audience about the state of knowledge at the time. Indeed, as in many other publications, Bernstein explains complex things in simple ways. This ability very much appealed to me (A.G.F.) from the first time I met Bernstein in 1962, during his visit to our lab at the Institute of Neurosurgery in Moscow.

There is another general aspect of the article that deserves to be mentioned. Although the article was written for an encyclopedia, Bernstein used it to try out new ideas, some of them still being formed. This was also typical of him. He continued to be a source of inspiration until the very end of his life.

Since I knew Nikolai Bernstein personally, some readers may feel it is appropriate for me to share my experiences of communicating with this extraordinary man and scientist. These readers may be disappointed, since I cannot add much to what has been written already (e.g., Feigenberg & Latash, 1996). Bernstein was an extremely modest and intelligent person, belonging, as we used to say in Russia, to the "old intelligentsia" who inherited and continued to carry on the best culture in the society despite the destructive efforts of Soviet power. In 1949, after Bernstein had received the highest award of the state (the "Stalin award"), politics radically changed with regard to biological science. He found himself deprived of his job and was prohibited from publishing. In particular, his politically innocent book *On Dexterity and its Development* (cf. 1996), already fully prepared for printing, was banned from publication.

Bernstein was more or less rehabilitated from 1957 onward, but never again fully accepted. In this respect, it is interesting to note that the 1958 reprint of the *Encyclopedia* no longer contained Bernstein's contribution. At that time his article was replaced by a much shorter contribution by A. Kogan, who did mention some of Bernstein's work, but the 1958 article on Movements is otherwise uninspiring.

I saw Bernstein on several occasions and even visited him with my colleagues at his modest flat at the time when he was working on the English edition of his book, *The Coordination and Regulation of Movements* (1967). When I met

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Bernstein, I was a junior scientist and basically speechless in the presence of my senior colleagues with whom Bernstein communicated (Mikhail Berkinblit, Victor Gurfinkel, Yakov Kotz, and Mark Shik, among others). I compensated for this by listening to them and reading Bernstein's works. I do not want to say that my behavior was constrained by some specific regulations dictated by the political system. Quite to the contrary, scientific discussions in our group were conducted in a democratic manner, only strengthened in the presence of such a personage as Bernstein.

Even to me, as a beginner in the science of motor control, it was obvious that Bernstein had managed to do a remarkable thing. He had integrated, in a systematic and logical way, the large bulk of knowledge on motor control accumulated before him. This remarkable step—the transformation of dissociated empirical data and existing ideas on movement production into one logical system—makes him the founder of modern motor control science. He also advanced experimental studies of movements, including human locomotion, by using existing and inventing new methods of movement recording (described in the present article). Most important, he formulated the major problems in motor control and thus defined the main focus of research for many scientists, including myself, for years to come. The present paper shows him on the brink of discovering these questions.

The ambiguous relation between control signals and motor output

The article "Movements" was written in 1929, long before Bernstein's main ideas on coordination were formulated. In the present article, one sees how these ideas begin to take shape. Except for several archaic terms and some questionable statements, Bernstein's text is sound, even, we believe, for contemporary readers, including specialists in motor control. He summarizes how German anatomy (e.g., Fick, 1904-1911) had applied the mechanical concept of degrees of freedom to the human body. He also explains why the passive mobility of the human body, defined by the number of mechanical degrees of freedom, is always greater than the active mobility, defined, in modern terms, by the number of control variables which the nervous system uses to govern movements (Feldman & Levin, 1995).

Bernstein uses the concept of synergy, which was defined and elaborated more clearly in his later publications (cf. Bernstein, 1935/1988). He explains why circular segments of movement trajectories are as rare as straight ones. Based on rather limited experimental data on movement trajectories as were available at the time, Bernstein concluded that movement trajectories are usually "smooth and rounded." His ideas were thus a precursor to the "smoothness principle," formulated in recent years by Hogan and Flash (1987). For rhythmic movements, this smoothness may be related to the fact, revealed by Bernstein, that their trajectories can be represented as the sum of two or a maximum of three harmonic oscillations (cf. Bernstein, 1927).

The section on Movement Dynamics is especially interesting since it shows the initial steps in Bernstein's reasoning which led him to the conclusion that the relationship between central signals to muscles and the actual motor output is ambiguous (cf. Bernstein, 1935/1988). This formulation is fundamental for the understanding of motor control. In particular, it rejects the notion, still shared by many contemporary motor control scientists, that movement kinematics may be directly programmed by the nervous system using "inverse dynamic" computations to specify muscle forces and torques. In the section on Movement Dynamics,

Bernstein just touched on this major conclusion by indicating that human movements are not guided exclusively by muscle forces but instead result from the interactions between different forces, including gravity, passive elastic, and reactive forces. Muscle force is thus only one of the many players in the complex game called movement.

Bernstein indicates that even muscle forces cannot be directly programmed by the nervous system, since also the relationship between the activation signals and the resulting muscle forces is ambiguous, because of muscle elasticity. Moreover, because of the proprioceptive feedback to motoneurons, muscle activation patterns cannot be specified by central commands independently from events in the periphery. Bernstein thus indirectly formulates the fundamental problem of finding the quantities called, in modern terms, the control variables which the nervous system may specify independently of the initial state of the system to produce intentional motor actions (cf. Feldman & Levin, 1995).

A solution to this problem may yield an answer to the question of how the nervous system can produce efficient goal-directed movements, despite all the ambiguities in the relationships between different levels of organization of the movement system. In the present article Bernstein did not offer a solution to this problem, but recognizing that there is a problem is a prerequisite for its solution. It is for this reason that the paper makes very interesting reading, as one sees Bernstein on his way toward the right questions in motor control.

Movements*

N.A. Bernstein

Movements[1] and the mobility of the human organism and its parts are phenomena of such diversity and multitude that it would be an insurmountable task to present them in an exhaustive account. One may say that each and every process in human life contains elements of movement. To have a reasonably well-founded approach to human movements, one needs: (a) to identify the basic, essential features that are inherent to every movement in general; and (b) to analyze each of these features with respect to human movement, identifying and specifying all features that are ubiquitous in human movement, and those that are of particular practical interest.[2] The following features are typical to any movement: movement proceeds in space and represents a series of changes in time; and movement is always induced by a combined action of forces whose sources may be quite various. The following review of human movements is based on these features.[3]

Movement Geometry

The human body is mobile as a whole, that is, it can move from one place to another ("locomotory mobility" or "locomotion") in walking, running, swimming, etc. Besides, the parts can move with respect to each other ("deformational mobility"). When performed by the efforts of the organism itself, locomotion cannot proceed without deformations. Therefore, we should start with a review of deformational mobility. Human locomotor mobility has no boundaries while deformational mobility is limited by the design of the body and the links between its parts.[4]

Connections Among Parts of the Human Motor Apparatus

The human organism has two types of connections: (a) kinematic connections, implying the impossibility of any deformation that would lead to separating one part from another (in this respect, the human body is similar to most machines except projectile ones, such as the bow, gun, or loom); and (b) molecular connections, implying the absence of parts that are connected to the organism by means other than molecular particle coalescence.[5] In this aspect, the organism differs from the overwhelming majority of machines in that it lacks parts that can fully rotate about their axes. This limitation of the deformational capabilities of the organism is compensated for by the enormous variety of partial deformations that are available. While kinematic links only allow for limited translational deformations, and molecular links only for limited rotational deformations, the variety of forms of mobility in the human organism exceeds by far that of most artificial machines created until now.

Degrees of Mobility and of Connectivity

The mobility of parts of the human organism with respect to each other is defined by two features: (a) the measure or degree of mobility; and (b) the limits of mobility. Let us mentally break down the human organism into parts that could, as a first approximation, be considered as nondeformable (e.g., the humerus, femur, tibia, or lower jaw). Let us address such elements as "links." First we need to define the "degree of mobility" (or "measure of mobility," "Bewegungsfreiheit").

Mechanically, a body that is not linked to any other body possesses maximal freedom of mobility since it can be moved anywhere and in any way without limits. The mobility of a body that is linked to other bodies by rigid links will, to a certain degree, be limited by these links; a measure of this limitation is called the "degree of connectivity." One can define the degree of mobility of a partially connected body by subtracting the degree of connectivity from maximal mobility (inherent to the body when it would not be connected to anything else).

The location of a nondeforming body in space is fully defined by the locations of three of its points which do not pertain to a single straight line.[6] Therefore, if three points of a body which do not pertain to a straight line are fixed in space, the body would lose all its mobility while its degree of connectivity would be maximal. The degree of connectivity would be smaller if not three, but only two points of the body are fixed. In this condition, the body would get some minimal freedom of mobility. If only one point were fixed, the freedom of mobility of the body would increase while its degree of connectivity would further drop.

One can use the following method to define quantitative measures of mobility and connectivity for bodies with different numbers of fixed points. Each point of a free body can move in space along three dimensions; movement geometry expresses this fact by saying that each point of a free body has three degrees of freedom of mobility. Therefore, if a single point of a free body is fixed, the body loses three degrees of free mobility, or in other words, three degrees of connectivity are being created. If a point within a rigid body is fixed, another point can rotate about the fixed point over a spherical surface; its location on the surface could be defined by two coordinates (e.g., latitude and longitude). Therefore, fixing a second point of a body provides it with two more degrees of connectivity or eliminates two more degrees of mobility. Two fixed points allow the body only one motion, that is, rotation about an axis passing through the two points, so that each

point off the axis moves along only one possible line, a circle, while its location on the circle can be defined by a single coordinate (for example, elevation). If such a third point is fixed, the body gets one more degree of connectivity which, as mentioned earlier, eliminates its mobility altogether. Thus the total number of degrees of connectivity of a rigid body is 3 + 2 + 1 = 6; this is also the number of degrees of mobility of a free body in space. These relations can be more clearly seen as follows:

Number of fixed points	No. of degrees of connectivity	No. of remaining deg. of freedom of mobility	No. of deg. of freedom of a separate point
0	0	6	3
1	3	3	2
2	5	1	1
3	6	0	0

Freedom of Mobility of Human Joints

Since the human organism is a single, intrinsically connected body, any of its mobile links has at least one point attached to an adjacent link. Therefore, the relative mobility of rigid links cannot exceed that which corresponds to three degrees of connectivity (as in the lower mandible with respect to the head, and in the humerus or the femur with respect to the trunk). The mobility of soft body parts (e.g., tongue and heart) cannot be captured in a number of degrees since, due to the compliance of its connections, one cannot speak about some of their points being fixed with respect to others. The degrees of connectivity (and therefore the degrees of mobility in rigid links) depend on the different design of the connecting joints. The following list summarizes the degrees of mobility and connectivity of the main joints of the human skeleton.

- 3 degrees of mobility (3 deg. of connectivity): temporomandibular joint, shoulder joint, metacarpophalangeal joint, hip joint, and acromioclavicular joint
- 2 degrees of mobility (4 deg. of connectivity): atlanto-occipital joint, humero-ulnar joint, carpo-ulnar joint, carpometacarpal joint of the thumb, and knee joint in a flexed position
- 1 degree of mobility (5 deg. of connectivity): atlanto-axial joint, humero-radial joint, ulnar-radial joint, interphalangeal joints of the fingers and toes, sacroiliac joint, knee joint in an extended position, talocrural joint, and talo-calcaneal joint
- 0 degrees of mobility (6 deg. of connectivity): cranial sutures.

Limits of Human Joint Mobility

The limits of mobility of links (see Figure 1) with respect to each other are not defined by the geometrical features of the joints, but by the design and compliance of the ligaments and the shape of the bone epiphyses. Hence there may be joints with three degrees but still very narrow limits of mobility (such as the acromioclavicular joint) and, vice versa, joints with a single degree but rather wide limits of mobility (such as the elbow joint). On the one hand, as mentioned earlier, link rotations cannot be limited by more than 360°. On the other hand, the actual range of mobility never reaches 180°, having a maximum value of 170° (in the knee joint). The largest average ranges for individual joints are as follows:

knee joint (passive)	170°
metacarpophalangeal joints	90–150°

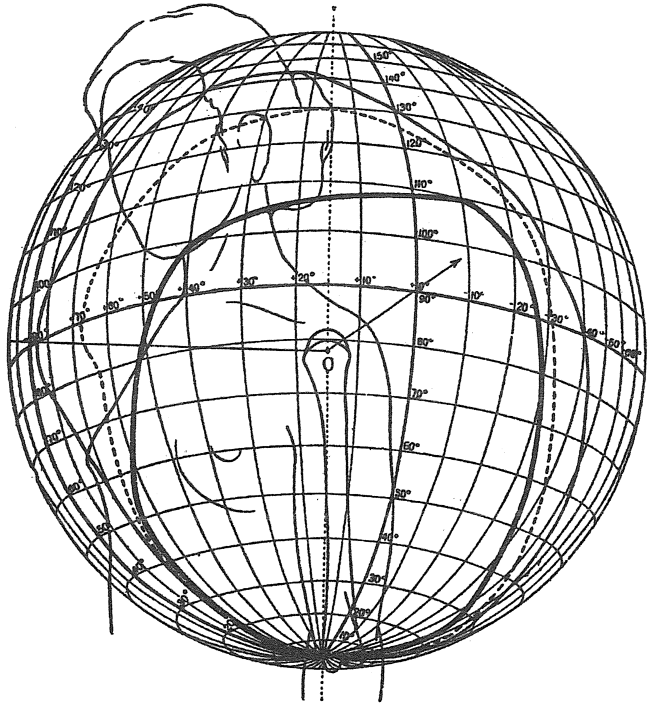


Figure 1 — Limits of mobility of the humerus in the shoulder joint. The internal, bold curve shows limits of humeral mobility if scapula is motionless; the dashed line shows limits of humeral mobility when scapula is free to move; the external, solid line shows limits of mobility when both scapula and clavicle can move (cf. Braune & Fischer).

knee joint (active)	140°
elbow joint	140–150°
ulnar-radial joint	120–140°
hip joint	130°
proximal interphalangeal joints	110–120°
acromioclavicular joint	105°
carpometacarpal joints	110°
metacarpophalangeal joint of the thumb	40–80°
digital interphalangeal joints	60–70°
carporadial joint	70°
talocrural joint	50–60°
carpometacarpal joint of the thumb	45–60°
atlanto-axial joint	40°
talocalcaneal joint	30–40°
atlanto-occipital joint	30°
carpometacarpal joint of the little finger	20–30°
lumbar intervertebral joints	22°
cervical intervertebral joints	15°
carpometacarpal joint of the middle finger	10°
thoracic intervertebral joints	8°

Freedom of Deformation of Human Body Parts

If a mobile link is connected by a partial connection to an absolutely motionless body (e.g., the wing of a semaphore to its pole), the degree of its connectivity would fully define the degree of its mobility. If a partial connection connects two mobile links (e.g., a pair of compasses), the degree of their connectivity defines only their relative mobility, but not the absolute mobility of each link separately. The measure of mutual relative mobility of two connected links is called the "freedom of deformation" of a two-link kinematic chain. Obviously, the freedom of deformation equals the freedom of mobility of one of the links with respect to the other if the other link is motionless. It is also obvious that the freedom of mobility of, for example, the femur with respect to the pelvis (if the latter is viewed as motionless), equals the freedom of mobility of the pelvis with respect to the femur, and they are both equal to the freedom of deformation of the two-link chain "pelvis-femur."

The freedom of deformation of more complex kinematic chains is defined by the variety of shape changes that are accessible to such chains. The freedom of deformation of an open, multi-link kinematic chain (i.e., a chain that breaks into two unconnected parts if any one of its joints is cut, such as "pelvis-femur-tibia-talus-calcaneus") is equal to the sum of the degrees of relative mobility of all the adjacent pairs of links that form the chain. The freedom of deformation of a closed kinematic chain (i.e., a chain that does not break into unconnected parts when one of its joints is cut, such as "humerus-radius-ulna") is smaller than such a sum. The open kinematic chain "pelvis-femur-tibia" has three degrees of freedom of deformation due to the hip joint, plus two degrees of freedom due to the knee joint. The following list summarizes the degrees of freedom of deformation of the main systems within the human body:

finger	2	head and neck	21
hand	33	head and lower mandible	3
lower arm plus hand	36	head & 2 upper vertebrae	6
whole arm from humerus	37	foot	11
whole arm from scapula	40	lower leg plus foot	13
arm plus shoulder joint	43	whole leg from femur	15
the whole body	191	whole leg from pelvis	18

It is important to note that the kinematic chains of the overwhelming majority of machines are of a closed nature. Thus their freedom of deformation is, in most cases, considerably smaller than the freedom of deformation of the human body. For reasons of comparison, the list below presents degrees of freedom of deformation for some machines.

Bicycle	5
Four-axix steam locomotive w/o front carrying wheels	10
Five-axix steam locomotive with a turning trolley	15
Car engine	1
Rotary printing machine	1
Typewriter (Underwood)	~60
Grand piano	480 [7]

The active mobility of the human organism is always smaller than its passive mobility. This is due either (a) to the weakness of the muscles that act on a

joint, so that its full mobility cannot be used (e.g., knee flexion, hyperextension of fingers), or (b) to the lack of appropriate muscles to perform a passively possible movement (e.g., finger rotation in the metacarpophalangeal joints), or (c) to the lack of appropriate innervations (e.g., hand rotation in the wrist joint), or, finally, (d) to the presence of insurmountable synergies (see later in the text) (i.e., cooperative innervations that do not allow for the separate active performance of certain components of complex system movements). For example, few people can flex their distal phalanges independently of the middle ones. The passive mobility of each vertebra with respect to an adjacent one has three degrees of freedom, whereas we are unable to perform movements in a single, isolated intervertebral joint, etc. There is even less freedom of deformation in common everyday movements which, as will be discussed later, almost fully consist of complex synergies.

Movement Kinematics

The Form of Human Movements

Even the simplest direct observation shows that the human organism does not use all the possibilities that are afforded by its mobility: A kinematic chain with two degrees of deformation, one end of which is fixed, can perform a straight movement of the other end. However, approximately straight movements of the endpoint of such a free system as the human arm (43 degrees of freedom of deformation) are rare, while perfectly straight segments do not occur at all. Abrupt angular changes of trajectories are similarly rare. As a rule, human movements are more or less smooth and rounded. One could have assumed that straight movements are absent precisely because they require a complex synergy while, due to the rotational design of most human joints, human movements should preferably demonstrate segments of circles. Nevertheless, precise observations show that circle segments are as rare in human movements as straight lines. (See later *Kinematics of Major Movement Syndromes*.[8])

There are very few quantitative studies of the shape of movement trajectories. Qualitative observations cannot be of much help in this area because, first of all, they are very inaccurate and subjective. Moreover, the following needs to be mentioned. Only during a rotational movement about a fixed axis (the human organism never performs such movements), or during straight progression (impossible for the organism), all points of a moving system perform movements of exactly the same shape. For any other movement, the shapes of trajectories of all the points of a system differ from each other. Hence, if no accurate, quantitative measurements are performed, one can easily miss points whose motions are in a certain aspect lawful, even when such points exist in the system.

However, to date some general features can be established. As mentioned earlier, the variety of active movements of separate systems within the human organism is incomparably smaller than the variety of passive movements that are available to the system on the basis of its freedom of mobility. If one compares the freedom of mobility of a link within the human body to a large valley, active trajectories available to the system could be compared to highways over the valley, occupying space that would be infinitesimally small compared to the whole surface of the valley (Figure 2).

To continue the comparison, one may say that the "valleys" of freedom of mobility of different systems within the human body are covered by "highways"

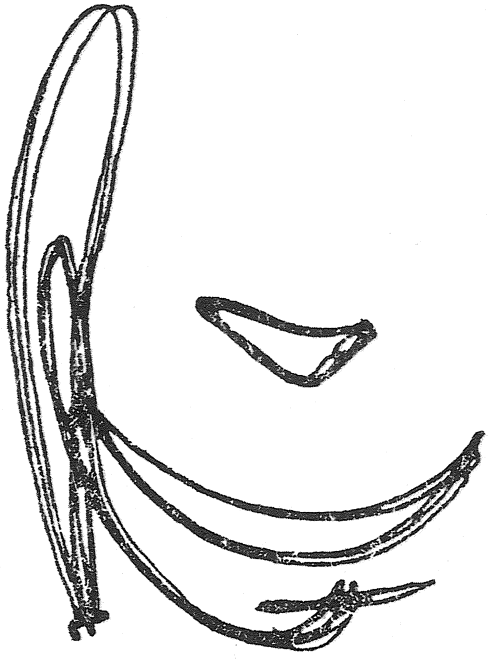


Figure 2 — Automatic nature of learned movements: Cyclogram of three successive strikes by a blacksmith (author's data).

with trajectories of active movements which have very different densities. Although there is a certain parallelism between the anatomical range of mobility of a system or a link, and the variety of available active movements (active mobility in the shoulder joint is richer than the active mobility in the ankle joint), the variety of possible active movements for a given system is primarily given by the innervational development of the motor centers of the system. The anatomical mobilities of the shoulder and of the hip are nearly identical, while the shoulder is incomparably more diverse in its active mobility. The fingers of the right and left hand have identical anatomical mobilities, but the variety of the active mobility is rather different between the hands. The anatomical mobility of the toes is only slightly lower than that of the fingers (the same freedom of deformation and only slightly smaller ranges of mobility); active movements of the toes, however, with the exception of the hallux, are limited to simultaneous flexion or simultaneous extension in all the phalanges.

The variety of active mobility does not seem to depend significantly on the number and variety of muscles surrounding the joints. The muscular fund of the hip joint includes more muscles and is more diverse with respect to their location as compared to the muscles of the shoulder joint, while the active mobility of the latter is much higher. The kinematic complexity of each individual trajectory of a human movement, that is, the complexity of its spatial form, is defined not by the measure of mobility of any given point of the moving system but by the magnitude of mass concentrated in this point. As a rule, if the mass is higher, the trajectory is more simple (Figures 3 and 4).

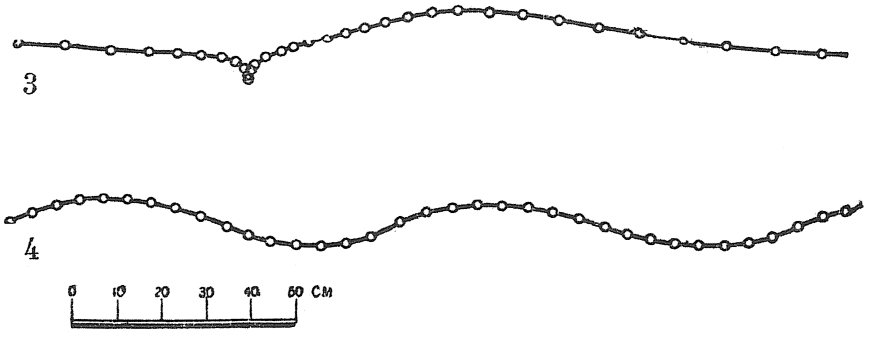


Figure 3 (top) — Trajectory of ankle joint motion during one double step in walking.
Figure 4 (bottom) — Trajectory of the center of mass of the body during walking.

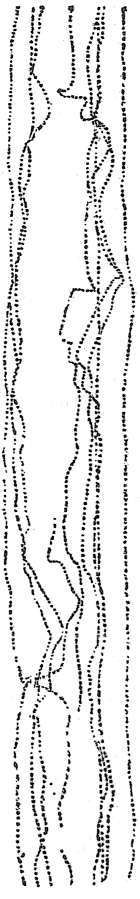


Figure 5 — Kymocyclogram of recharging a rifle (author's data).

This explains the great mobility of the hand and the fingers which are rich in freedom of deformation and highly individualized innervation, and are poor with respect to mass. Figure 5 shows a kymocyclogram of recharging a rifle[9] (author's record)—an example of an automatic movement of high complexity. Both the variety of movement trajectories and their complexity decrease significantly, even in richly innervated systems, under the action of human movement automation. Figures 2 and 6 illustrate the very high degree of similarity of successive automatized movements.[10]

Movement Velocities

Movement velocities along the trajectories have also been studied only rarely. The highest movement velocities of parts of the human body are reached by the distal ends of the extremities during a swinging motion in the proximal joint: by the hand during shoulder movement and by the foot during hip movement. During throwing movements, the hand can reach velocities of up to 20 m/s (72 km per hour); during fast running, the velocity of the foot reaches only slightly lower values.

In rhythmical movements, velocities are smaller and they do not depend on the tempo of the movement but on its amplitude: With an increase in movement tempo, the amplitude commonly drops, and in such a case the velocity barely increases. In normal physiological conditions, velocities of the hand and foot in humans commonly reach 5 to 6 m/s. The maximum tempo of movements is directly related to the mass and the moment of inertia of the moving part. Finger movements show the highest tempi (up to 8 to 10 movements per second), while the trunk shows the lowest tempi, when it swings in the hip joints.

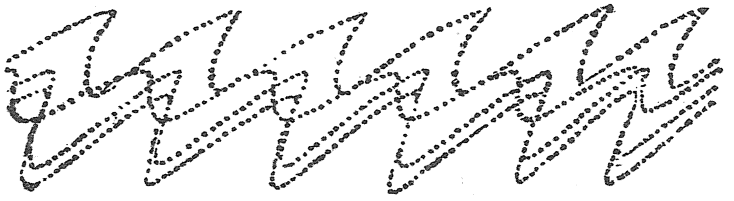


Figure 6 — Sawing a board with a handsaw: The kymocyclogram demonstrates a high degree of automation (author's record).

Rhythmical Movements

Until now, formulating a general kinematic law has only been possible for rhythmical movements. The exact formulation of this law contains certain mathematical complexities; therefore, in this article only some general ideas are presented.

Any oscillatory rhythmical movement can represent either a simple pendular (sine) oscillation, or the sum of simple pendular oscillations of different frequencies that are simultaneously performed by the moving body. For this sum to remain rhythmical, all the individual oscillations should have a common rhythm. In other words, the durations of full cycles (or "oscillation periods") of the individual oscillations should relate to each other as 1 : 1/2 : 1/3 : 1/4, etc. Obviously,[11] any rhythmical human movement or, more precisely, movement of every point of a moving organ, can be represented as such a sum. Such movements involve walking, running, turning a handle, numerous labor movements (filing, blacksmith strike, and hand movements while playing piano), pathological movements (tremors and clonus), etc. In all these movements, the main rhythm is represented by the so-called "main oscillation" whose period equals unity; additional oscillations with periods of 1/2, 1/3, 1/4, etc., are superimposed on the main one. The amplitudes of the summed oscillations can certainly be very different; obviously, when the amplitudes of additional oscillations are much smaller than the amplitude of the main oscillation, the structure of the movement is simpler.

The aforementioned kinematic law of the process of rhythmical human movement states that, for different points of a moving human organ and for different movements, the amplitudes of additional oscillations may have different values with respect to the amplitude of the main oscillation. They are smaller, and therefore the movement is simpler, (a) when the mass of the moving and its moment of inertia are larger, and (b) when the tempo of the movement is higher. Hence, during movements of a large moving system (e.g., the movement of a leg during walking), the movements of the centers of mass of parts of the system will be simpler, i.e., closer to a pendular-like oscillation, than the movements of the joints of the same system, while the movement of the center of mass of the whole system will be simpler than the movements of the centers of mass of its parts (see Figure 7). Let us explain this with examples. The amplitudes of motion components of different points on the leg (with respect to the main component, whose amplitude is considered to be 100%), are shown in Table 1 for normal walking.[12]

Table 2 presents the relations among movement components during an accelerated tempo of piano octave movements (performed by a renowned virtuoso). The mechanical structure of a rhythmical movement is, as a rule, simpler for faster

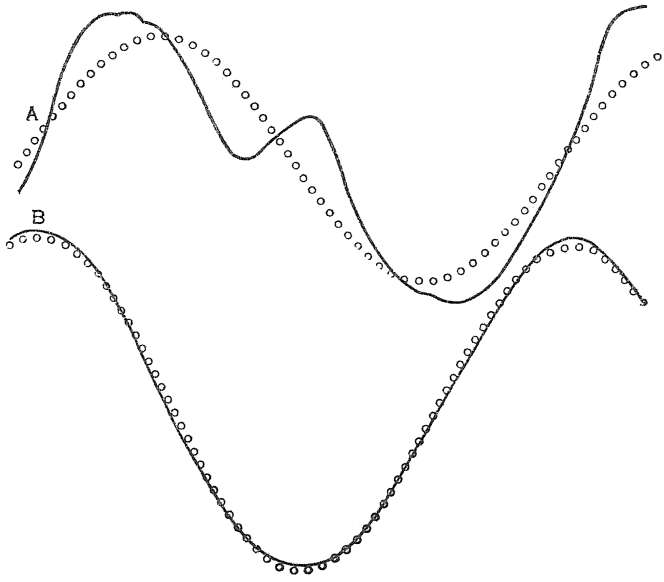


Figure 7 — Movements of separate points of the leg during walking and the main sine waves of these movements. Solid lines = movements; open circles = main sine waves. (A) the knee; (B) the leg's center of mass.

Table 1 Relative Amplitudes of Motion Components in the Leg

Moving point	Amplitudes (%) of components 1st	2nd	3rd	4th
CM of upper leg	100	26.1	4.1	2.8
Knee joint	100	20.6	3.2	2.9
Tip of foot	100	22.5	2.1	1.3
CM of foot	100	20.0	2.1	1.5
CM of shin	100	4.7	0.7	0.3
CM of whole leg	100	3.8	0.7	0.5

CM = center of mass.

movements and larger moments of inertia of the moving mass. (For the kinematics of major motor syndromes, see *Running* and *Speech*.) Studies of the kinematics of human movements in normal and pathological cases are of great diagnostical interest (see later in the article). Let us mention here that clinical experiments demonstrate that fine deviations of human movements from normal patterns, which at early stages of a disorder cannot be seen by the naked eye, are clearly revealed by recording these movements with a sensitive technique. In the near future, this should make studies of human movement kinematics an important tool in clinical practice.[13]

Table 2 Relationship Among Movement Components in Piano Playing

Tempo (strikes/sec)	Amplitude of main component (cm)	Amplitude of 2nd component (cm)	(%)
2.2	2.67	2.55	95.0
4.6	1.80	0.49	27.2
6.0	1.58	0.168	10.6
7.8	1.04	0.007	0.7

Movement Dynamics

Probably no other field has witnessed so many errors and hasty conclusions as the area of human movement dynamics.[14] This is understandable: As noted above, the motor system of the human body is one of the most complex free mechanical systems that exist, with immeasurable variability, presently beyond adequate mechanical explanation. For a mechanicist, the human body is a conundrum of complex, unsolvable problems. Naturally, a physician is not insured against terrible mistakes in this area (which is exceptionally complex for a mathematician, but looks simple to a physician who is unaware of its complexity). Therefore, we need to consider very carefully the main facts of human movement dynamics, without touching on the more complex, secondary phenomena.

Internal and External Forces

The body of a moving organism is constantly under the action of external and internal forces. External forces include the following: the force of gravity, forces of resistance of the environment (air, water during swimming, etc.), reactive forces, and a whole variety of changing forces which act from outside (pushes, hits, etc.). Internal forces include molecular forces of particle attachment, elastic forces—which emerge during muscle activation, ligament stretching, compression or bending of cartilage or bone—and forces of friction that occur during movement in all the moving parts of the organism. If there is a long-lasting balance among all these forces, the organism is in a state of equilibrium. If forces are not in equilibrium, i.e., if the resultant force and its moment are not zero, the organism starts a movement which fully depends on the magnitude, direction, and moment of the resultant force.[15] Since all the forces mentioned (excluding the force of gravity) are changing forces, a modification in any of them can induce the initiation of, or a change in, movement of the organism.

From the point of view of movement mechanics, it is only essential to know whether a force, or a resultant, is external or internal with respect to the organism or its parts (the kinematic chain), independently of the origin and source of the force. Thus we need to give a definition of "external" and "internal" forces with respect to a kinematic chain. According to the third principle of mechanics, the action of any force is balanced by an equal counteraction, directed along the same line as the original force but in the opposite direction. If the point of application of a force and the point of application of the counteracting force are within one chain,

the force is viewed as internal with respect to that chain. For example, for the chain that includes *the whole arm from the shoulder down*, the force of tension of the m. brachialis is internal, while the force of tension of the m. pectoralis major is external. With respect to the system *forearm and hand*, the force of tension of the m. brachialis is external.

However, force generated by the m. brachialis and acting on the humerus is transmitted along the bone to the ligaments of the shoulder joint, i.e., to points that are external with respect to the system *the whole arm*. The reaction force of this transmitted force is acting at the center of mass of the whole kinematic chain attached to the shoulder joint. Hence, any force which is internal with respect to a given kinematic chain creates an external force, always of the same nature, a force acting along a straight line that connects the center of mass of the kinematic chain and its point of attachment.

In other words, internal forces within a kinematic chain can act at the center of mass of the chain only by pulling or pushing it along a line that connects it with the point of attachment of the chain. The moment of a force which passes through a point equals zero with respect to that point. Thus we have come to the main theorem of muscle dynamics: The torque generated by a muscle internal with respect to a certain kinematic chain is different from zero with respect to all internal points of that system, and equals zero for all points outside the system.

Muscle Torque. Action of Muscles Internal or External to a System

The aforementioned theorem of muscle dynamics gives an infallible route for finding out whether muscles at a certain joint participate in a movement or a position under consideration, and if so, to what degree. It is sufficient to define the torques within a moving system with respect to each joint. If the torque with respect to a certain joint is zero, the muscles of that joint do not participate in the movement; if the torque is different from zero, its magnitude directly characterizes the measure of muscle forces at the joint.

For the human body as a whole, each muscle is internal. Hence the torque that is generated by each individual muscle (and, consequently, the torque of all muscles taken together) equals zero with respect to an external point of support. Therefore, if only one external point of support is available, none of the body muscles are able to move the body's center of mass otherwise than along a straight line that connects the center of mass with the point of support. In other words, if only one external point of support is available, a person can move only under the action of an external force (weight, push, etc.). If there are several points of support, internal forces within the body will definitely allow for the generation of a non-zero torque, at least with respect to one of the points of support, and then any movement is possible.

Parametric, Tonic, and Contractile Forces

From the point of view of movement physiology, forces acting within a given kinematic chain should be classified in a different way. According to their physiological importance, forces can be divided into three groups: (a) forces originating outside the organism, i.e., forces whose presence and magnitude do not depend on the organism (force of gravity, wind, external pushes, etc.); (b) forces emerging within the organism and fully depending on the location of its parts and their state of movement, so-called parametric forces (forces of extension of ligaments and tendons, elastic strains in bones and cartilage, internal friction in muscles, forces

of inertia of the links, etc.); and finally, (c) forces that emerge within the organism and can change independently of the location of its parts and their state of movement—these are the muscle forces (tonic and contractile).

In each movement state of an organ, the organism is unable to affect independent forces, whose origins are outside the organism, or parametric forces, which can only follow a single, unchangeable curve of magnitude during a given movement. Only the forces of muscle tension[16] are subjected to permanent control by the organism. Thus,[17] from the physiological viewpoint, muscle is not the only force generator of the organism, and even not its main source of forces. It is the only controllable engine. The human motor system can be compared to a sailing boat with an auxiliary steam engine—the muscle system. To make this comparison more precise, it must be mentioned that the "steam engine" is not weak by itself, usually able to move the boat against any wind or hurricane. Nevertheless, the whole development of motor mechanisms, both in general ontogenesis and during the acquisition of new skills, boils down to a permanent improvement of the skill to exploit wind and sails and to save fuel. In studies of walking of healthy humans, one can see very clearly how much use is made of the "free" forces in walking, and how active muscle work is minimized.

Relation Between Muscle Tension, Shortening, and Movement

The dynamic action of a muscle depends on its tension. However, as should be clear from the previous, tension is not necessarily due to muscle activation. A nonactivated muscle is an elastic, strained structure, like a ligament, a fascia, or a bone, but with different characteristics of extensibility and elasticity. The main difference between the function of muscle and the function of ligament is only that for the ligament every extension corresponds to one and only one tension, while for the muscle the same extension may correspond to different tensions depending on the degree of its activation. Hence, muscle activation is a way not to induce muscle tension but to modify it.[18] A change in muscle tension leads to a change in the resultant of the many forces (independent, parametric, and muscular) which act at a given kinematic chain (first causal step), while this change in the resultant force leads to a change in the movement of the kinematic chain as described earlier (second causal step).

Generally speaking, movement in a kinematic chain changes the distances between the points of attachment of the muscles within the chain. If these points move away from each other, the muscle stretches, whereas if the points move toward each other, the muscle shortens because of its elastic properties. However, because of the very complicated interaction of forces acting on the system, it is absolutely impossible to predict in a general form how an increase in the tension of a muscle would influence the movement of the system. Hence it is impossible to predict whether the muscle will stretch or shorten as a result of the system's movement.[19]

Therefore, in physiological conditions, the contraction[20] of a muscle is not directly related to an increase in its force and represents only one of the possible consequences of movement of the whole system; it is equally possible the muscle will stretch or show no changes in its length. There are no situations in which muscle shortening is the cause of a movement. Situations in which muscle shortening is an unambiguous and obligatory consequence of a movement that is induced by activation of that muscle are the simplest, most schematic cases (e.g., muscle contraction in a myograph; isolated, local muscle excitation by Faraday currents, etc).

An Indicator Graph of Muscle Work

Mistakes that come from the failure to distinguish between activation, tension, and contraction of a muscle depend on the confusion between the notions of muscle force and muscle work. Maybe the best way to explain the actual relationships between these magnitudes is through Figure 8. The abscissa shows changes in muscle length (shortening – stretch), and the ordinate shows changes in muscle tension (contraction – relaxation). Each muscle process can be illustrated on such an "indicator graph" by a curve. If after some time the muscle returns to the same state of length and tension from which the process started, the curve will be closed as shown in Figure 8. The area surrounded by the curve corresponds to muscle work. Figure 8 and the lower loop of the 8-shaped form in Figure 9 show the work performed by the muscle along the curve encircling the area in a counterclockwise direction. The upper loop of the 8-shaped form in Figure 9 shows the work that is absorbed by the muscle along the curve encircling the area in a clockwise direction.

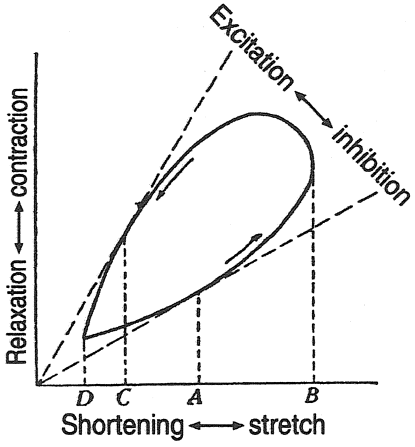
The measure of muscle activation is characterized by the ratio of muscle tension to the corresponding muscle stretch (since both passive and activated muscle contract during stretch and relax during shortening): The ratio will be higher the more activated the muscle is. Therefore, on the graph, excitation is characterized by an increase in the slope of a straight line connecting a point on the graph with the origin of the coordinates; inhibition is characterized by a decrease in this slope.

In Figure 8, ordinate D corresponds to the smallest length and tension of the muscle. From D to A, the muscle is stretched, its tension increases, and its measure of excitation drops. From A to B, all three values increase, i.e., the muscle is activated, its tension increases, but its length increases as well. From B to C, the measure of muscle excitation continues to increase, the muscle shortens, and its tension drops. From C to D, muscle excitation and tension drop while the muscle is shortening.

A more complex case is illustrated in Figure 9. Here an increase in the level of excitation occurs at the A-B segment during continuous stretching of the muscle. Starting from Point B, the excitation starts to drop, while the muscle is still being stretched until Point C. Shortening occurs from Point C to Point D during a continuous decrease in both tension and measure of excitation. (This illustration is taken from a study of hand movement in the strike of a piano key.) Thus, muscle excitation may begin and end during a stretching phase, while all the energy of excitation will transfer into potential elastic energy of the stretched muscle, and this potential energy will be turned into mechanical muscle work a few fractions of a second later, during the shortening phase.

Motor Mechanisms

Muscle excitation depends only on the activity of the central nervous system and in no way on the state of the moving organ. However, muscle tension inevitably depends on the state of its stretch, i.e., on the movement of the organ to which the muscle belongs. Therefore, muscle tensions within a given organ are, on the one hand, causes of its movement, and on the other hand, consequences of the same movement. Hence, in human movements there is a closed chain of interactions between forces (muscle tensions) and positions: The former influence the latter, while the latter influence the former.



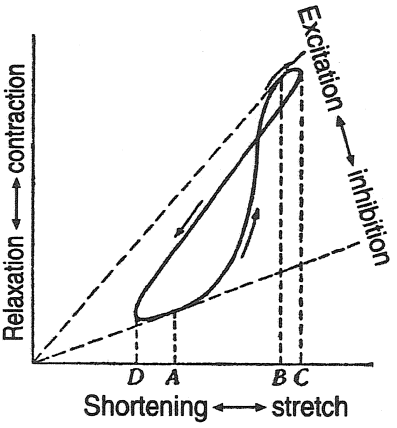


Figure 8 (left) — The indicator graph of muscle work.
Figure 9 (right) — The same graph for a more complex case.

Such chains of interactions are expressed in mechanics by second-order differential equations; however, their analysis is very complicated. It is only possible to indicate the most basic features of such equations defining human movement. Each equation contains coefficients or parameters. For example, in a simple quadratic equation $x^2 + px + q = 0$, the parameters are p and q. The parameters of equations defining human movement are the constant values of the moments of inertia of the links, the coefficients of elasticity of the ligaments, coefficients of friction among parts, etc. It is for this reason that the forces emerging in the centers of gravity of the links, in ligaments, in interacting parts, in the sarcoplasm, etc., have been termed "parametric forces."

The difference between a differential equation and a simple algebraic equation, as the one mentioned earlier, is that an algebraic equation has one or several separate solutions (for example, a quadratic equation has two solutions), while a differential equation has an infinite number of solutions. Which one of these solutions will take place, or in other words, which movement will follow a given change in muscle excitation, does not depend on the form of the equation and not on its parameters but on the so-called "initial conditions." In a differential equation for the motion of a part of the human body, such initial conditions may include, for instance, initial position and velocity of the body part. A change in the initial conditions can completely change the kinematic effect (the whole external movement pattern), even if the defining differential equation, and therefore the law governing the changes in muscle tension, remains exactly the same.

Muscle Force Scheme and Initial Conditions of a Movement. Proprioceptive Mechanisms and Proprioceptive Correction

It follows from the preceding that knowledge of a movement leads to knowledge of its muscle force scheme. However, the inverse solution is impossible: Knowledge of a muscle force scheme is insufficient to predict the ensuing movement, because one and the same scheme can generate a large variety of movements depending on the initial conditions. One may say that the variety of movements is larger than the variety of muscle force schemes.

Because of this, if the organism's abilities were limited to turning on the innervation for a certain muscle force scheme, it would have no guarantee that the scheme would lead to the required movement in time and space. To perform a kinematically defined movement, it is not enough to have a fixed set of centrifugal impulses. It is also necessary to have control impulses that are centripetal. These are defined by the aforementioned initial conditions; they can introduce corrections into the originally activated innervational scheme, depending on the particular spatial motor situation.

Such impulses are the so-called "proprioceptive impulses" that emerge in the nervous endings within tendons, joint capsules, deep layers of the skin, etc. Because of the proprioceptive reflexes, there is an interaction localized within the central nervous system that is analogous to the mechanical interactions between muscle tension and position, as described earlier. Central motor impulses lead to changes in the motion of a kinematic chain, while these changes, through proprioceptive reflexes, modify and correct the central motor impulses. Therefore, once again, this interaction should be characterized by a set of differential equations not lower than the second-order. However, in contrast to the earlier discussion, the actual formulation of these equations is impossible, given the present state of our physiological knowledge.

The action of proprioceptive reflexes allows for the so-called "proprioceptive coordination" of discrete movements (the term "coordination" is in a way a Sammeltopf where the most various motor mechanisms are being deposited). This type of coordination takes place during all movements of a healthy human, starting[21] from the moment of myelinization of the dorsal columns. This coordination is partially affected during diseases of the dorsal columns (ataxia). However, complete elimination of this coordination does not lead to ataxia but to the complete inability to perform any movements at all. Presently, the process of this coordination has been studied best in rhythmical movements (for example, the scratching reflex[22]).

Spatial shortening of a muscle induces reflex inhibition of its antagonists (see later) and excitation of its protagonists (see later). Therefore, innervation of a muscle group is accompanied by denervation[23] of the opposing group. In contrast, a quick muscle stretch excites the muscle itself (muscle rebound, Rückstoss). In particular, a quick flexion of a finger leads to stretching of the finger extensors and gives rise to an opposing extensor rebound (Lewy). We still know very little about proprioceptive coordination during nonrhythmic movements.

The Systemic Character of Motor Innervations

Our present knowledge of the place of origin and the structure of the muscle innervation movement scheme is very poor. Whether due to the wide irradiation of proprioceptive impulses, or because of the structure of the innervational scheme itself, healthy humans never demonstrate an isolated excitation of one muscle, or even of a group of neighboring muscles. The possibility of isolated innervation, which is beyond doubt for the spinal motor cells, has been proven neither for the motor layers of the cortex of large hemispheres nor for the subcortical nuclei with motor functions (striatum, pallidum, and red nucleus). Central excitation always has a systemic nature, and simultaneously involves large muscle groups. This fact has been coined "muscular synergy." Like "coordination," this term is still devoid of any physiological or localizational meaning.[24]

Synergies

Some types of synergy probably consist of inborn systemic innervations, common in all humans (e.g., wrist extension during clenching the fingers). These synergies occur inevitably during the innervation of a certain muscle group. Other types of synergy apparently emerge steadily, during the process of maturation of a certain motor mechanism. They are only seen during the activation of certain muscle groups within specific constellations (e.g., the synergy of forearm pronators and supinators with the flexor-extensor system of the fingers during writing). This group of synergies is rightfully seen as the source of a large variety of motor skills.

A special place among synergies is occupied by so-called "associated movements" that occur in adjacent kinematic chains during a purposeful movement of one of the chains. A significant proportion of associated movements represents rudiments of large synergies that used to play a functional role (e.g., arm swinging during walking which has been preserved since the times of quadrupedal walking).[25] Sometimes, the results of motor-innervational irradiation of excitation during the acquisition of a new motor skill can also be seen as belonging to this group (children sticking the tongue out during writing or drawing; the inability of novices to do different movements with both hands during piano playing, because of the associated movements, etc.). The largest functional synergies, which involve the whole body, include locomotor movements such as walking, running, swimming, etc. Static synergies which make standing and sitting possible are comparably large. There is indirect clinical evidence which implies that synergies are localized in subcortical brain centers.

Rhythmical Innervations

The temporal sequence of systemic innervations is also defined by the activity of the central nervous system. As we have seen, the time order of innervations and denervations during the simplest rhythmical sequences is regulated by simple proprioceptive reflexes. For more complex rhythmical sequences, involving large muscle groups, the mechanism of rhythm regulation is yet unclear, although there are reasons to believe that rhythmical coordination is largely defined by subcortical activity (in particular, of the pallidum).

The Innervational Structure of Human Movements

To control movements, the central nervous system has a rather finely distributed muscular-skeletal apparatus, characterized earlier. Connections between the central nervous system and the muscular-skeletal apparatus are realized peripherally via centrifugal nerves—originating in the ventral roots of the spinal cord and in sympathetic nuclei, and ending at neuromuscular plates—and by centripetal neural fibers—extending from the connecting surface of tendons and muscular perimysium, to the spinal ganglia. Using these connections, the central nervous system realizes all the movements that are available to the human organism, no matter which centers of the nervous system they originate from.

Thus, in the majority of complex human movements, controlled simultaneously by a whole bunch of motor areas within the central nervous system, peripheral nerves conduct very complex impulses which emerge as a result of the superposition of numerous central impulses of different origin. Spinal motor reflexes demonstrate the simplest structure: A corresponding motor impulse emerges in the ventral roots of the spinal cord in response to an excitation that comes from

the body periphery. However, all these reflexes excite more than one muscle. Only hypothetical local reflexes (Eigenreflexe, Spiegel) are likely to be limited to activating a single muscle (the tendon reflex of the quadriceps, extending the knee; of the shoulder triceps; etc.). As a rule, spinal reflexes recruit a whole bunch of muscles with synergetic action.

From the point of view of the participation of individual muscles in a certain human movement, muscles that contribute to the movement get particular names. Muscles whose function is similar to that of a certain muscle are termed "agonists" of that muscle (for example, for elbow flexion, the m. brachialis is an agonist of the m. biceps). Muscles whose functions differ from those of a given muscle, but which play a supporting role during a certain movement, are called "protagonists" or "synergists." For example, while lifting the arm (arm elevation), muscles of the shoulder blade (m. serratus, m. trapezius, etc.) work as synergists of the deltoid muscle, although their common motor function is very different from that of the deltoid muscle. Finally, muscles whose function is opposite to the function of a given muscle are called its "antagonists."

One should emphasize that in the overwhelming majority of cases, both protagonism and antagonism do not represent permanent functions of one muscle with respect to another muscle. During every individual movement, the distribution of roles among muscles changes. In particular, during shoulder adduction the m. pectoralis major is an antagonist of the m. deltoideus, while during shoulder flexion both muscles are mutual protagonists. During elbow flexion the m. brachialis and the m. biceps brachii are agonists, while during forearm supination they are protagonists, and during flexor pronation they can even become antagonists.

Spinal motor reflexes usually involve a whole system of agonists and protagonists. For example, the reflex of hand withdrawal involves a whole system of muscles. It is even more important to note that one and the same peripheral excitation can induce pain reflexes of very different structures depending on the original position of the reacting extremity. When fingers are stimulated by a painful induction current, shoulder flexion will occur if the arm is in front of the body, and extension will be seen if the arm is behind the body. In lower vertebrates, spinal reflexes can demonstrate a rhythmical, alternating pattern of impulses between agonists and antagonists (e.g., the wiping reflex in the decerebrate frog). It is hard to say whether such a rhythmical alternation of spinal origin is present in humans.

More complex movements of healthy humans are usually performed with participation of the motor area of the cortex of the large brain hemispheres. This area uses impulses that are transmitted to peripheral neurones via the pyramidal tract. However, there is not a single movement that is only performed by the pyramidal system. The cortex never participates in movement generation isolated from subcortical motor centers, which are connected to the spinal cord via the extrapyramidal system.

The degree of participation of each of the two systems can differ in different movements, but it is already clear that, on average, the role of the extrapyramidal system in a normal movement is larger than that of the brain cortex. It is quite probable that there exist movements performed only by the extrapyramidal system, without any cortical participation. Movements involving pyramidal innervations are still frequently called "voluntary" or "volitional," although both terms, because of their subjective nature, should have long ago been discarded.[26] It would

be more accurate to speak of cortical movements that are controlled by both the cortex and the extrapyramidal system, as contrasted to subcortical or extrapyramidal movements that are innervated exclusively by the striato-pallidar apparatus.

In a baby, cortical movements emerge only several months after birth because of the delay in the myelinization of the pyramidal tract. So, during the first months of life, babies innervate their movements through the extrapyramidal system only. In the adult human, three forms of interaction between the cortex and the subcortical apparatus can be identified:

1. Apparently cortical movements ("voluntary," according to the old terminology): This group includes all singular, complex impulses, as well as chain movements constructed of dissimilar complex impulses. Examples are movements of an artist painting a canvas, movements of assembly or disassembly of a mechanism, complex sorting, the movements of a surgeon during an operation, etc. In all these movements the cortex clearly dominates, while extrapyramidal innervations only provide the general background and foundation. This group also involves movements that are performed while learning a new motor skill such as walking, speaking, writing, etc.

2. Movements dominated by extrapyramidal innervations ("automatic" or everyday movements): This group involves the overwhelming majority of human movements: walking, speech, writing, routine professional movements, etc. In these movements the participation of the cortex is so reduced that the actor is unaware of individual impulses. Psychologically, these movements can be seen as direct transitions from an image (the visual image of a letter, the auditory image of a word, etc.) to its reproduction. All movements of this group are not inborn but elaborated by more or less slow exercise, leading to their automation. It is interesting to note an aspect that is characteristic of these movements and makes them different from other movement groups. In these and only these movements, individual motor features of a given subject are displayed. Walking is colored by gait, writing by individual handwriting, speech by accent, piano playing by touch, etc. Movements of this type can also display constitutional differences in movement styles. The large degree of participation of the subcortical apparatus is reflected in the smoothness of these movements, their well-balanced architecture, a tendency to use large, well-coordinated synergies, etc. Cortical domination leads to angular, abrupt, accurate, but less elegant movements.

3. Movements in which the cortex does not seem to participate at all, although it can participate in them: Such movements are called "automatisms." They include breathing, blinking, yawning, stretching, defecation, etc. Movements of this group are inborn; they exist in babies from the first day of life. Automatisms differ from reflexes, first by their higher complexity and second by the fact that they are not excited from the periphery but from central structures, due to causes that emerge within the organism itself. In diseases of the extrapyramidal system, new pathological automatisms can emerge, such as tics, athetoses, chorea, etc. (see later, *Movement Pathology*).

Methods of Study of Human Movements

In a brief review, it is impossible to present a comprehensive account of all the numerous methods that have been used to study human movement. Therefore only the main ones will be described, particularly those having clinical significance.

Prephotographic Methods

Among the prephotographic methods of human movement studies, the method of pneumatic recording with a so-called "Marey capsule" has retained its importance. It is hard to find a movement that was not studied with pneumatic recording. A particular method, developed by Bruzhes in the USSR and by Johnen in Germany, is important in the study of muscle tension: A cuff with increased pressure is wrapped around the segment to be studied (just as in the measurement of blood pressure), and connected by a tube to a Marey capsule. Bulging of contracting muscles increases the pressure in the tube and moves the drawing pen in the Marey capsule.

A relatively large number of recording methods use mechanical transmission of movement to a recording device. The Weber brothers studied knee flexion during walking by connecting the foot to the hip joint with a tight tape and recording the distance between the two points. Isserlin and later Lewy studied finger movements using a thread to connect the tip of the finger with a pen drawing on a rotating drum. An analogous method was used by M. Fischer and Wodak to record arm displacement during reflex changes in muscle tone. Recently the same method has been used to record the knee reflex. Sommer built a so-called three-dimensional apparatus (Figure 10) which uses a lever transmission to record the displacements of the fingertip (or the tip of the foot) along all three coordinates.

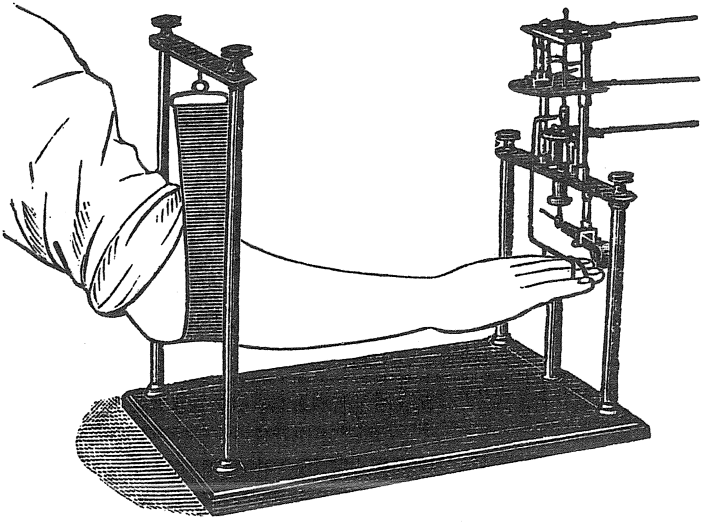


Figure 10 — Three-dimensional apparatus by Sommer.

In clinical practice, methods are particularly popular in which the body part to be studied records its own movement, without any transmission. Among these are the method of gait study which uses step marks left by greased shoes on a paper walkway, and the method of cefalography, that is, the recording of head displacement with a sharp stylus fixed on the top of the head, drawing on charred paper spread above the subject's head. The method for recording changes in joint angles, developed by Filimonov, is very promising: Wooden compasses are attached to the area of the joint in such a way that they open or close during joint

extension or flexion; the angle between the compasses is recorded with the help of electrical contacts.

Cinematography and Rapid-Cinematography

The development of photography has opened new, wide resources for the study of human movement. At the very dawn of instantaneous photography, Muybridge in America, Anschütz in Germany, and Marey and Demeny in France made series of instantaneous photos of movements of humans and animals. Experiments by Marey and Demeny led to the emergence of cinematography, which remains a most valuable method of movement study, particularly in cases where external, qualitative impression is more important than high precision. A cinematographic camera is now a compulsory element of a well-equipped neurological, psychiatric, orthopaedic, or ocular clinic.

Lately, rapid-cinematography, or the time magnifier (Lehmann, Labrélie), has become more and more popular abroad. It can make 250 to 300 shots per second, instead of the 16 to 18 typical of the regular cinematographic camera, thus allowing for detailed studies of fast movements (Ascher, Nouneberg). The same principle of rapid-cinematography was used earlier, by Bull, to study movements of small animals. He reached amazing frequencies of recording, up to 10,000 shots per second.

Chronophotography and Cyclography

Besides their high cost and complexity in operation, cinematographic methods are inadequate when high precision is required. Therefore, in parallel to these methods, starting from the 1880s, another group of methods has been developed known as "chronophotography" (Marey, Braune, Fischer, Frémont) and "chronocyclography" (Gilbreth, Thun, Tikhonov, Kekcheev). Specifically, in these methods a rapidly successive series of photographic shots is made of a moving object, recorded on one and the same stationary photographic plate rather than on sequential segments of a moving film as in cinematography.

These methods give a nice visual image of the movement trajectory but also make the photographic plate look cluttered. Hence it is preferred to make photographic images not of the whole object but of selected lines or points (Figure 11), which can be done by placing brightly lighted segments or electrical bulbs on the body which is dressed in a dark suit. With such a modification, the image acquires contrast and can be used for the most precise measurements. The drawback is that shots are perfectly readable only for locomotor movements, with the object continuously moving in the visual field of the camera. For small, complex, and repetitive movements whose trajectories always come back to the starting point, these methods cannot be used.

Kymocyclography

During the last years, Bernstein developed the method of "kymocyclography" which eliminates these drawbacks. In this method, the motionless plate is replaced with a slowly and continuously moving film, unlike cinematography where the film movement is fast and jerky. (The method of kymocyclography was used to make the photographs shown in Figures 5 and 6 of this article.) The method allows the filming of any small and fast movements with frequencies of 600 shots per second and higher, and with the possibility of very precise measurement (up to 1/10th of a millimeter and 1/100,000th of a second).

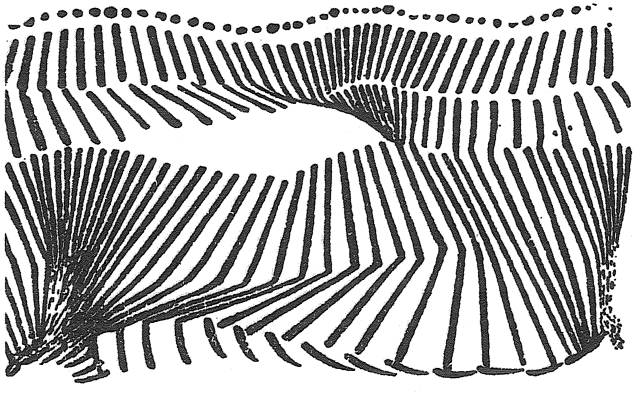


Figure 11 — A cyclogram of walking made by Marey.

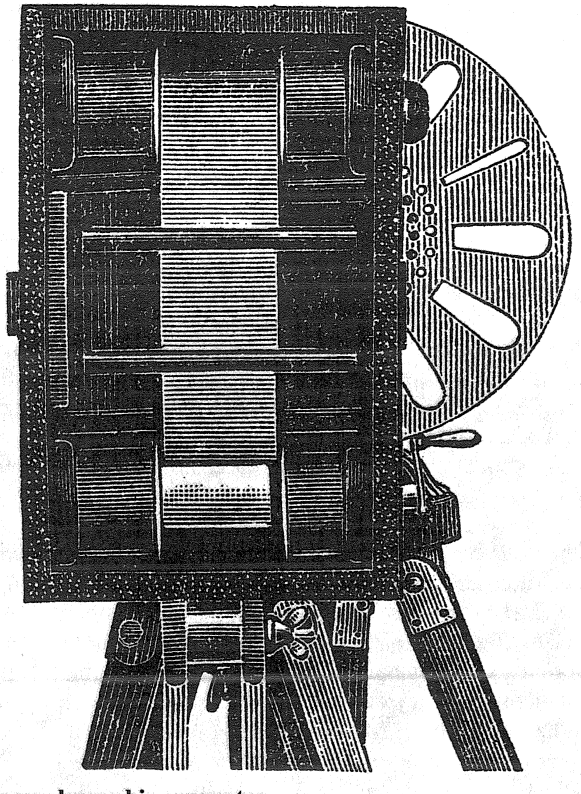


Figure 12 — Kymocyclographic apparatus.

The kymocyclographic apparatus is shown in Figure 12. It consists of a camera with a photographic lens and a device for steady film motion, a rotating shutter, a power distributor supplying voltage to light bulbs, and tapes with bulbs. The bulbs are 2 mm in diameter and 6 to 7 mm long; thus they do not present a perceptible additional load for the subject. Kymocyclography can also be used for studies of three-dimensional movements in space (not only planar movements, as with cin-

ematographic records). To achieve this, Bernstein suggested the method of mirror recording which allows the spatial coordinates of a moving point to be defined in a very simple way.

In the future, cyclography and kymocyclography are likely to play an important role in clinical studies. Cyclography gives very valuable data in clinical studies of pathological gait. Presently, kymocyclography is used to record tremors, adiadochokinesis, tonic arm reactions, knee jerk, etc. The possibility of getting precise measurements with these methods allows us to calculate the forces that act during human movements, and hence, to proceed to studies of muscle-force schemes[27] and differential equations of human movement (see earlier). For this purpose, methods of cyclogrammetry have been developed (Fischer, Bernstein) which allow muscle dynamics to be determined from measurements of records of human movement.

Electromyography and Electrical Methods of Movement Recording

One also has to mention electrical methods of recording the processes that accompany human movements. First of all, this group includes electromyography (Einthoven, Yudin, Samoilov), i.e., recording action currents from activated muscles with the help of a string galvanometer. Until now this method remains the only one that provides reliable information on the processes of muscle excitation in an intact organism. Among other methods of electrical recording that deserve the most serious attention of clinicians is the as-of-yet unnamed method developed by Popov. The apparatus consists of a high-frequency oscillatory circuit built with cathode tubes, as in a radio set. The capacitance of this circuit is defined by the position of a plate placed in front of the subject. Infinitesimally small motion of a studied body part with respect to the plate changes its capacitance, which is immediately reflected in the current in the circuit. With a cathode amplifier these changes are transmitted to a recording galvanometer. The accuracy of Popov's apparatus is truly amazing and is of the order of thousandths of a millimeter.[28]

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Editor's Notes

*The paper was translated by Mark L. Latash and edited for clarity. It appeared in the *Bol'saja Medicinskaja Enciclopedija* [Grand Medical Encyclopedia], Volume 8, pp. 451-474 & 479-480. Moscow: Medgiz (1929).

[1]The present paper was written before Bernstein's paper on Coordination (1930) in the same encyclopedia (cf. Beek & Meijer, 1999). It is interesting to campare the rather traditional tone of the beginning of the present paper with Bernstein's jumping into the unknown in 1930.

[2]Note how Bernstein, typical Soviet scientist as he is at the time, gives both theoretical and practical reasons for research.

[3]Bernstein's starting point, movements in space that proceed in time and are induced by a combination of forces, belongs to the then dominant tradition of German materialistic mechanicism. Braune and Fischer's (1895-1904) state-of-the-art understanding of walking was of great importance to Bernstein, and was used as the source of Figure 1. Fischer (e.g., 1897) introduced the mechanical notion of "degrees of freedom" into anatomy. This notion was made popular in human anatomy by his student Rudolf Fick (cf. 1904-1911): "Mechanicists quantify *freedom of movement* [Bewegungsfreiheit] as so-called *degrees of freedom*" (Vol. 2, p. 76, our translation, italics in original). In Western Europe, mechanistic functional anatomy remained dominant until the late 60s, particularly through the textbooks of Benninghoff and Goerttler (e.g., 1964 & 1967).

[4]In hindsight, it is amazing to see how Bernstein in 1929 still wanted to start with the parts in order to arrive at the whole. This he reversed in 1935 (1935/1988), adopting views from German *Gestalt* psychology. Those who expect to be thrilled to see the development of Bernstein's views on coordination in this section on Movement Geometry are in for a disappointment. Much of the information Bernstein uses in this section derives from cadaver specimens. As Fick wrote, "*the degree of freedom of the joint in question is smaller in the living, and cannot be larger than that in the cadaver specimen.* Research on cadaver

specimens, therefore, always reveals the *maximum* freedom of movement" (Vol. 2, p. 271, our translation, italics in original).

[5]This is the exact translation (Mark Latash, personal communication). In the human body, all parts are held together by molecular forces and not by, say, magnetic fields.

[6]Didactically, Bernstein's presentation of "degrees of freedom" in human movement is more attractive than Fick's classical text (Vol. 2, p. 85). Bernstein discusses the "degrees of freedom" of an object in terms of the number of independent variables (coordinates) fully describing its spatial configuration. Note that this number is independent of the nature of the variables we choose: They may be Cartesian coordinates, angles, or even torques or energies.

[7]Even today it remains difficult to count degrees of freedom in the human body. In the present paper it is amusing, and not without relevance, that we learn that the grand piano has 289 more degrees of freedom than the human body. Bernstein and Popova's analysis of piano playing also appeared in 1929 (to be published shortly in Bernstein's Heritage). In the paper on piano playing, Bernstein for the first time moves in the direction of coordination dynamics. The difference between that paper and the first sections of the present paper is striking. According to Iosif Feigenberg (personal communication), Bernstein was quite impressed by Popova. They were also related, since she was married to his brother.

[8]Italic terms refer to other articles in the same encyclopedia. The reference here is to the last section of "Movements," written by I. Filimonov, on the Pathology of Movements (published again in the 1958 edition). In the present article, Filimonov's section is not included.

[9]Note that this example belongs to a very old tradition. In 1599, Count John of Nassau started a military drill for the movements that were needed to handle the arquebus and the musket. Jacob de Geyn's 1607 pictures of these movements went through many editions and were used in most Western European military circles (Parker, 1996). Also for Braune and Fischer, the foot soldier offered an important motive for studying movement (Flesher, 1997).

[10]Although clearly aware of variability over repetitions, in the late 1920s Bernstein emphasizes their lawful, automatic appearance (cf. 1927). In 1935 (cf. 1935/1988) he had made a *Gestalt* switch when, looking at the same figures (cf. Figs. 2, 5 & 6), he emphasized their variability.

[11]Like so many intellectuals (cf. Note 12), Bernstein often uses "obviously" for things that are not obvious at all, at least not at first sight. The argument presented here is developed in detail in his 1927 paper.

[12]Obviously, the empirical reality is not as simple as Bernstein's theoretical scheme. Note, however, that he is honest enough to just give the data.

[13]This is the main point of Bernstein's 1954 paper on Coordination Disorders (cf. Wagenaar & Meijer, 1998).

[14]It is easy to recognize that Bernstein is now "warming up." So far, the paper summarized the state of the art. In the present section, he will hint at the fact that Braune and Fischer's (1895-1904) idea—that there are straightforward relations between the will, the central signal, muscle activity, and movement—may be wrong.

[15]The general idea that imbalance in forces results in movements has been known since Aristotle. Since Newton, it was also known that equilibrium in the force field does not preclude the body from moving (by inertia). Mechanically, Bernstein's statement is thus imprecise. Nevertheless, Bernstein repeated in a paper in 1940, when he was discussing the control and coordination of walking, that movement occurs whenever the "equilibrium in the force field is destroyed" (1940/1967, p. 62; cf. Bongaardt, 1996). It is tempting to speculate that at some point in the development of his theory, he started to see disruption of the

equilibrium as a mechanism for control. In the λ-model, the control system resets the equilibrium state of the system so that the body is out of equilibrium and thus moves to a new equilibrium state (Feldman & Levin, 1995).

[16][M.L.L.] Bernstein uses here, and further in the article, a Russian word whose meaning is very ambiguous. It can either mean force or a characteristic of force-generating properties (similar to "strain"). In the translation, the equally ambiguous term "tension" is used.

[17]This "thus" is a stylistic jewel. On the one hand, muscles are all we can control, so they are of paramount importance. On the other hand, we have to exploit the independent forces, as had been said before, e.g., by the Weber brothers who advised soldiers to let gravity do its work on the swinging leg (cf. Flesher, 1997), or Von Haller who advised to lean forward when walking against the wind or climbing a mountain (Mary Flesher, personal communication). Braune and Fischer (1895-1904) had rejected the analysis of the Webers because they held that muscles are under permanent control of the will. Logically, there is nothing wrong with Bernstein's "thus." Historically, it shows his departing from the Braune and Fischer tradition.

[18]Again (cf. Note 17), we see a turning away from Braune and Fischer (1895-1904). Until his paper with Popova on piano playing (1929), Bernstein just adopted Braune and Fischer's mechanicism, while working on the cinematography of movements. The present section reveals how much Bernstein had become aware of the ambiguities in the relationship between muscle activation and the resulting movement.

[19]This appears to be an overstatement, and there are more to follow (e.g., "There are no situations in which muscle shortening is the cause of a movement" in the next paragraph). In our opinion, Bernstein's use of overstatements reveals he was very much aware of the fact that he was now treading on new ground. He really wanted to make his point, even in an encyclopedia, and even at the cost of overstating his case.

[20][M.L.L.] Bernstein uses a Russian word that means both contaction and shortening. Part of this paragraph is based on a word play. In the translation, the better fitting English equivalent is used on each occasion.

[21]In ontogeny, that is.

[22]Bernstein's understanding of the scratch refles in the decerebrate frog (cf. Beek & Meijer, 1999, Note 5) will lead him in his next contribution to the *Grand Medical Encyclopedia*, on Coordination (1930), to conceiving coordination in terms of low level autonomy (cf. Sechenov, 1863/1965).

[23][M.L.L.] Bernstein uses this term to imply a drop in excitation (just as "innervation" means an increase in excitation).

[24]With hindsight, it is interesting to see how Bernstein notes the vagueness of the terms "coordination" and "synergy" in his 1929 paper, and then sets out to give them precise meaning (cf. 1935/1988).

[25]Apparently, it escapes Bernstein in this paper that there can be a functional role for arm-leg synergies in human walking (cf. Van Emmerik & Wagenaar, 1996).

[26]Note that in 1929, Bernstein would have regarded the title page of the journal *Motor Control* as obsolete.

[27]Although this text is not explicitly inconsistent with what he wrote in the sectoin on Movement Dynamics, one gets the impression that Bernstein is now back where he started: German mechanistic materialism. This may be due to the fact that he felt so much at home with measuring movement, that in writing the present section he just relived the success of the time of building his equipment (not bothering about the theory). To us, it is clear that the vista he offers in his section on Movement Dynamics is not yet a stable part of his own understanding of the organization of movements.

[28]One is left with an odd feeling of dissatisfaction. To the contemporary reader, the paper beings and ends with the least interesting parts: the mechanical definition of degrees of freedom, and by now obsolete equipment for measuring kinematics. In between, we find sections on Movement Kinematics and on Motor Mechanisms, which contain interesting information and sometimes hint at new insights, but fail to be really inspiring. It is the middle section, Movement Dynamics, which makes fascinating reading. After Kuhn's book on the Structure of Scientific Revolutions (cf. 1983), some may have believed that scientific revolutions come in a single blow. They do not. There is no doubt that 1929 is the year in which Bernstein started to ask the right questions about the organization of movements. The present paper allows us to look into the kitchen. But what we see is a strange combination of boredom, promising jewels, and confusion. And there is no recipe to ensure the quality of the final meal. Such, we contend, is the nature of scientific revolutions.

[29]These are the original references of the whole article on Movements, including Filimonov's section on Pathology of Movements (cf. Note 8).

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Acknowledgments

The editors gratefully acknowledge Irina Sirotkina, Moscow, for her help in obtaining the text of the paper, and Natalija Dmitrieva, Elvira Kopp, Susanne Oehlschläger, Witalij Sayko, and Jörg Streiter, all from the Federal Institute of East European and International Studies, Köln, Germany, for their help in obtaining the pictures, and Micha Mirsky for comments on the manuscript. Iosif Feigenberg, Jerusalem, offered some fascinating insights into historical aspects of the paper. Sander de Wolf, Faculty of Human Movement Sciences, Vrije Universiteit, gave much-appreciated assistance in producing the final version of the paper.

This work was supported (A.G.F.) by the National Science & Engineering Research Counsil (Canada).

Accepted for publication: December 14, 1998